A Research Proposal to the CLIVAR-Pacific Component of NOAA's Climate and Global Change Program

Subseasonal Predictability of the Coupled Tropical Indo-Pacific

Duration:	Three years
Total Support Requested:	$219,360
Requested Starting Date:	February 1, 2004

Prashant D. Sardeshmukh
Principal Investigator (PI)
Associate Director
NOAA-CIRES
Climate Diagnostics Center
R/CDC, 325 Broadway
Boulder, CO 80305-3328
(303) 497-6248
Prashant.D.Sardeshmukh@noaa.gov

Matthew Newman
Co-PI
Research Scientist
NOAA-CIRES
Climate Diagnostics Center
R/CDC1, 325 Broadway
Boulder, CO 80305-3328
(303) 497-6233
Matt.Newman@noaa.gov

Cécile Penland
Co-PI
Physical Scientist
NOAA-CIRES
Climate Diagnostics Center
R/CDC1, 325 Broadway
Boulder, CO 80305-3328
(303) 497-6234
Cecile.Penland@noaa.gov

Randall M. Dole
Institution Representative
Director, NOAA-CIRES Climate Diagnostics Center
R/E/CD, 325 Broadway
Boulder, CO 80303-3328
(303) 497-5812
rmd@cdc.noaa.gov

Subseasonal Predictability of the Coupled Tropical Indo-Pacific

Abstract

There is growing recognition of tropical biases in climate models that have persisted despite many years of coordinated model development in the climate research community. One possible cause of these errors is the misrepresentation of shorter-term tropical variability in the models. In particular, there has been much recent research into the MJO-ENSO connection. The primary goal of our proposed project is to construct a linear inverse model (LIM) of the coupled tropical atmosphere-ocean system from past observations that is useful for simulating, predicting, and diagnosing tropical anomalies on subseasonal scales. We have recently presented (in Winkler et al 2001, Newman et al 2003) an atmospheric LIM of weekly variations of extratropical streamfunction and tropical diabatic heating that is excellent at representing the simultaneous and time-lag statistics of these quantities. Penland and collaborators (e.g. Penland and Sardeshmukh 1995b) have already demonstrated the usefulness of the LIM technique for diagnosing and predicting seasonal tropical SST variations. The forecast skill of these atmospheric and oceanic LIMs in the Tropics is competitive with that of much more comprehensive models, and suggests that coupling them will improve upon both. We will construct such a coupled LIM with its state vector representing the dominant EOFs of weekly anomalies of the tropical circulation at five tropospheric levels, the dominant EOFs of the column-averaged and column-varying heat sources Q1 and moisture sinks Q2, and the dominant EOFs of SSTs in the Indo-Pacific domain.

We will then use this coupled LIM to diagnose the variability and predictability of the coupled tropical system on weekly and longer time scales. We are particularly interested in determining (1) the average predictability as well as the case-to-variations of predictability of each model variable at each grid point, (2) the 4-D structures of the coupled circulation-heating-SST eigenmodes of the system and their relation to structures deduced from tropical wave theory, and (3) the form and impact of the air-sea coupling on subseasonal tropical variability, including but not restricted to the MJO. We will also repeat the entire analysis on existing coupled GCM output from the NCAR CSM2 and CMIP2+ models, to assess to what extent the relationships among the atmospheric and oceanic LIM variables are correctly represented in comprehensive coupled models.

P.I.	:	Prashant D. Sardeshmukh
Co- P.I.	:	Matt Newman and Cécile Penland
All at:		NOAA-CIRES Climate Diagnostics Center R/CDC, 325 Broadway, Boulder, CO 80305-3328
Total cost:		$219,415
Budget period	:	Three years, starting February 1, 2004

1. Motivation and Background

Despite many years of coordinated model development in the climate research community, some climate model biases in the Tropics have proved remarkably difficult to eradicate. These include a mean cold SST bias, a too equatorially confined structure of ENSO variability, and substantially erroneous frequency power spectra. **Figure 1** illustrates the problem for 8 global coupled models participating in the Coupled Model Intercomparison Project (Meehl et al. 2000) (CMIP2+). Compared to observations, the model spectra of the dominant EOF of tropical Pacific SST variability show very different total power, and the time scales in which it is concentrated. They also appear more sharply peaked than the observed spectrum, which, although estimated from a shorter record, is nonetheless smoother and approximates the spectrum of red noise with an 8-month correlation scale. Such a spectrum is suggestive of a damped linear system with broadband stochastic forcing, i.e forcing with a much shorter correlation scale. And indeed one possible suggested cause of the climate model errors has been the misrepresentation of shorter-term tropical variability in the models (e.g., Fedorov et al. 2003). In particular, there has been much recent research into the MJO-ENSO connection. The primary goal of our proposed project is to construct a model of the coupled tropical atmosphere-ocean system that is useful for simulating, predicting, and diagnosing tropical anomalies on subseasonal scales in observations and in climate model simulations. A correct representation of important coherent (and therefore, in principle, predictable) subseasonal tropical phenomena such as the MJO, whose simulation and prediction remain problematic in most weather and climate models, is of course also important in its own right.

To avoid repeating the errors of many previous "forward" modeling attempts, our coupled model will be a linear inverse model (LIM), derived from the observed statistics of weekly tropical variations over the last 50 years. Linear inverse modeling may be broadly defined as extracting the dynamical properties of a system from its observed statistics, as described for example in Penland and Sardeshmukh (1995b) (see also Penland 1989, 1996; Penland and Ghil 1993; Delsole and Hou 1999, Winkler et al 2001, Newman et al 2003). The procedure and its strengths and pitfalls are discussed at length in these papers, so we will only provide its bare essentials here for convenience of later discussion. In any multidimensional statistically stationary system with components x_i, one may define a timelag covariance matrix $\mathbf{C}(\tau)$ with elements $C_{ij} = \langle x_i(t+\tau)\, x_j(t) \rangle$, where angle brackets denote a long term average. In linear inverse modeling, one assumes that the system satisfies $\mathbf{C}(\tau) = \mathbf{G}(\tau)\mathbf{C}(0)$, where importantly $\mathbf{G}(\tau) = exp(\mathbf{B}\tau)$ and $\mathbf{B}$ is a constant matrix, and uses this relationship to estimate $\mathbf{B}$ given observational estimates of $\mathbf{C}(0)$ and $\mathbf{C}(\tau_0)$ at some lag τ_0. In such a system any two states separated by a time interval τ are related as $\mathbf{x}(t+\tau) = \mathbf{G}(\tau)\mathbf{x}(t) + \varepsilon$, where ε is a random error vector with covariance $\mathbf{E}(\tau) = \mathbf{C}(0) - \mathbf{G}(\tau)\mathbf{C}(0)\mathbf{G}^T(\tau)$. Note that the system need not have Gaussian statistics for these relations to hold. However, for its statistics to be stationary, $\mathbf{B}$ must be dissipative, i.e its eigenvalues must have negative real parts. In a forecasting context, $\mathbf{G}(\tau)\mathbf{x}(t)$ represents the "best" forecast (in a least squares sense) of $\mathbf{x}(t+\tau)$ given $\mathbf{x}(t)$, and $\mathbf{E}(\tau)$ represents the expected covariance of its error. Note that for large lead times τ, $\mathbf{G}(\tau)\mathbf{x}(t) \Rightarrow 0$ and $\mathbf{E}(\tau) \Rightarrow \mathbf{C}(0)$. Note also that unlike multiple linear regression, determination of $\mathbf{G}$ at one lag identically gives $\mathbf{G}$ at all other lags.

We have constructed LIMs from just atmospheric data (ALIM; Winkler et al 2001, Newman et al 2003) and from just oceanic data (OLIM; Penland and Sardeshmukh (1995b), Penland and Matrosova (1994, 1998)). The ALIMs have been constructed separately for winter and summer seasons, in a reduced EOF space representing weekly averaged streamfunction anomalies at 750 hPa and 250 hPa and weekly-averaged column-integrated tropospheric diabatic heating anomalies. During winter, 37 EOFs were retained, whereas 50 EOFs were retained for summer; in both cases this truncation retains more than 90% (70%) of the variability in regions of large streamfunction (heating) variability. Similarly, the OLIM shown below is constructed from yearround three-month running mean SST anomalies, determined from the HADIST dataset for the years 1950-2002; 30 EOFs (which explain greater than 90% of the variance) have been retained. [This OLIM differs only in some quantitative details from the OLIM presented by Penland and collaborators, who used a different dataset, time period, and EOF truncation.]

Particularly in the Tropics, both models are competitive with fully nonlinear GCMs, which have nominally $O(10^6)$ degrees of freedom. The OLIM is used to make realtime SST forecasts, and is included in the *Experimental Long-lead Forecast Bulletin*. For the ALIM, **Figure 2** shows that for week 2 tropical diabatic heating forecasts in both winter and summer, the skill of the weekly ALIM compares well with the version of the MRF used operationally in 1998 at NCEP (MRF98). Moreover, MRF98 forecasts of tropical heating are actually considerably worse than those of the ALIM over the west Pacific, an important region of air-sea coupling on subseasonal time scales, where the MRF98 has poor skill as early as week 1 (not shown) and no skill by week 2.

One benefit of LIM is that predictability can be assessed directly from it. For example, one can show quite generally, for any forecast variable at any grid point, and regardless of whether or not the distribution of that variable is Gaussian, that for a perfect model the expected correlation ρ_∞ of ensemble-mean forecasts with observations is given by $\rho_\infty^2 = S^2/[1+S^2]$, where $S = s/\sigma_f$ is the forecast signal to noise ratio (Sardeshmukh et al. 2000). For the LIM, both s and σ_f can be determined a priori for every initial condition (Newman et al. 2003); the resulting S can be used to estimate the theoretical (that is, perfect model) skill of the LIM.

Figure 3 shows that the actual ALIM skill is comparable to the theoretical skill, though still somewhat smaller. In the ALIM, the predictable variations of signal are associated with variations of the initial state projection on the growing singular vectors of the ALIM's propagator, which have relatively large amplitude in the Tropics. At times of strong projection on such structures, the signal to noise ratio is relatively high, and the Northern Hemispheric circulation is not only potentially but also actually more predictable than at other times (Newman et al. 2003). But there is clearly much dynamical information that is missing in our simple variable set. In particular, we have included no detail of the vertical structure of the diabatic heating, despite its potential importance to the propagation of the tropical circulation anomalies. Moreover, we have not included moisture flux anomalies which can precede convection. It seems clear that an extension of the ALIM to additional levels, including the vertical structure of both Q1 and Q2, is a necessary next step.

Similarly, actual OLIM skill is similar to but lower than the theoretical skill (**Figure 4**). Interestingly, although the skill of forecasting the broad dominant pattern of tropical central/east Pacific SST (i.e., the leading EOF) is high, along a narrow equatorial belt in the east Pacific both actual and potential skill are reduced. This is a result of the large signal in this region being overwhelmed by even larger noise on the seasonal time scale. A key unanswered question is whether this is truly noise, or whether it represents either missing variables (including atmospheric) or whether instead a higher fraction of predictable variability in fact exists on the *weekly* timescale. For example, **Figure 5** shows that there is considerable variance of weekly SSTs in this region and also in the IndoPacific warm pool area. Thus, some of the seasonal variance in these regions may be a residual of weekly variability. In a seasonal OLIM, possible weekly predictable variability is not resolvable, but it could be in a weekly OLIM, especially when coupled to the atmosphere.

This point is emphasized in **Figure 6**, which shows the two growing singular vectors of the seasonal OLIM for a lag of τ=8 months. It is interesting how their initial structures are only mildly different but their final structures are radically different. This implies that minor differences in the initial states in the western Pacific can give rise to radically different ENSO evolution. To improve our long-lead ENSO forecasts, then, we must improve our representation and prediction of these initial anomalies in the western Pacific. In the seasonal OLIM formalism we would say we need to "get the stochastic forcing right" in the warm pool area. In the weekly coupled LIM we would say we need to "get the weekly variability and weekly predictions right".

Although it would be useful to improve the ALIM and OLIM independently of each other as described above, it is clear from the above that a more comprehensive model involves coupling the two together. From a forecast standpoint alone, coupling the ALIM and OLIM together should improve the skill of each. For example, equatorial heating anomalies at the dateline should evolve differently depending upon the SST conditions. If the impact of air/sea interactions upon MJO propagation is significant, then a coupled LIM (CLIM) should have a better MJO forecast than an ALIM. Conversely, some of the climate noise in the seasonal OLIM may be due to atmospheric variability which is predictable on the weekly timescale.

But perhaps as useful is the insight to be gained from a coupled LIM into the real-world coupling between the atmosphere and ocean, since the structure of LIM allow us to quantify these feedbacks. For example, Winkler et al. (2001) defined their state vector **x** as

$$\mathbf{x} \equiv \begin{bmatrix} \psi \\ \mathrm{H} \end{bmatrix} , \tag{1}$$

where ψ was anomalous streamfunction and **H** was anomalous tropical diabatic heating. The linear inverse model could then be expressed as

$$\frac{d}{dt}\begin{bmatrix} \psi \\ \mathbf{H} \end{bmatrix} = \begin{bmatrix} \mathbf{B}_{\psi\psi} & \mathbf{B}_{\psi\mathbf{H}} \\ \mathbf{B}_{\mathbf{H}\psi} & \mathbf{B}_{\mathbf{HH}} \end{bmatrix}\begin{bmatrix} \psi \\ \mathbf{H} \end{bmatrix} + \begin{bmatrix} \mathbf{F}_{s_\psi} \\ \mathbf{F}_{s_\mathbf{H}} \end{bmatrix} \tag{2}$$

where $\mathbf{F}_{s_\psi}$ and $\mathbf{F}_{s_\mathbf{H}}$ were the white noise forcing of ψ and **H**, respectively. By including **H** explicitly in **x**, it became possible to diagnose how tropical heating impacts streamfunction variability (Winkler et al. 2001) and predictability (Newman et al. 2003) through $\mathbf{B}_{\psi\mathbf{H}}$, and vice versa through $\mathbf{B}_{\mathbf{H}\psi}$. We expect a similar analysis on the extended atmosphere-ocean state vector will prove equally enlightening.

To carry out this analysis, it is critical to have a complete dataset of not only SSTs and atmospheric circulation, but also the more difficult to determine quantities of the apparent diabatic heat source Q1 and moisture sink Q2. It is well known that notable differences which exist in the divergent wind field between reanalyses in the Tropics (e.g., Newman et al. 2000) can negatively impact estimates of both heat and moisture budgets. That the error in the analyzed wind fields is predominantly in the divergent component of the wind, and not in the rotational component, is consistent with the fact that the large-scale vorticity analyses produced at different data centers are in much better agreement than the corresponding divergence analyses. One way to correct the analyzed divergence is by constraining the winds to minimize imbalances in both the mass and vorticity budgets, thus enforcing dynamical consistency upon the divergent circulation. We have applied this approach, known as the "chi-problem" (Sardeshmukh 1993; Sardeshmukh et al 1999) to the four-times daily NCEP-NCAR reanalysis for the years 1949-2003. The resulting altered wind fields have then been used to compute estimates of the four-dimensional Q1 and Q2 fields. **Figure 7** shows that in the TOGA-COARE winter in the IFA region, the so called "chi-corrected" Q1 and Q2 profiles are in better agreement with observations than is the NCEP reanalysis, with a nearly identical estimation of the deep convective heating profile Q1 and low-level Q2. Further analysis by Lin et al. (2003) shows that the chi-corrected Q1 field captures the enhanced "top-heaviness" of the vertical profile of heating during the mature phase of the MJO. Thus, we expect that the inclusion of these Q1 and Q2 datasets in the coupled LIM should help in simulating and predicting MJO variability.

2. Research Tasks

The results shown in Figures 1–7 suggest that an empirically-derived dynamical model of the coupled atmosphere-ocean system in the Tropics may prove to be as, if not more, useful than current coupled GCMs in diagnosing subseasonal variability and predictability. Note, of course, that LIM is not meant nor intended as a replacement for coupled GCMs; as an empirical model, it does not allow us to experiment with the physics of the climate system, nor does it help us understand what would happen in the presence of external forcing (such as anthropogenic change) on the system. However, since LIM provides both the dynamical operator **B** and an estimate of the noise forcing, it is an extremely powerful *empirical* technique. As briefly discussed above, this allows not only a forecast model (which provides a hard test for the success or failure of the LIM technique), but more important a determination of relevant dynamical structures, the quantification of different feedback processes to these structures, and the differing levels of predictability associated with these structures. That is, the LIM shows us the *form* of the dynamical system that must be simulated correctly by coupled GCMs. LIM thus provides an important baseline for diagnosing error within coupled GCMs, as well as evaluating the relative importance of these errors. For example, which are the most important sources of error (and how do they interact): errors of atmospheric dynamics within the AGCM including those which act to provide the atmospheric noise forcing of the ocean, the ocean dynamics, and/or the coupling between the AGCM and OGCM?

Our basic research goal thus broadly consists of two parts: development of the CLIM and then its application to diagnosis of tropical variability and predictability. To fully develop the CLIM we must do the following:

1. Currently we have ALIMs only for winter and summer. We will construct coupled LIMs for the entire year, and extend the data coverage to over 50 years.
2. At present the ALIM state vector consists of 250 and 750 mb extratropical streamfunction and column-averaged tropical diabatic heating. To modify the model for the tropical problem, we will consider tropical streamfunction and velocity potential anomalies at 200, 400, 600, 850 and 1000 mb and also the tropical Q1 and Q2 anomalies in the upper and lower troposphere instead of just the tropospheric column average of Q1 used previously. The training and verification datasets of Q1 and Q2 will be derived from dynamically consistent wind convergence fields (using the "chi-correction" technique developed at CDC) to compute the vertical velocity needed for Q1 and the moisture convergence needed for Q2. Note that column-integrated Q2 anomalies are equivalent to P-E (precipitation minus evaporation) anomalies.
3. We will additionally extend the state vector to include tropical SSTs. Weekly SST data is only available for the 1981-current period from NCEP (Reynolds et al 2002). Our preliminary analysis shows that this dataset is sufficient to determine a SST-only LIM. Thus, we will construct a CLIM for the 1981-current period. Clearly, however, more data is useful in increasing the

number of degrees of freedom (and hence the resolution) of the LIM. The second singular vector of the OLIM (Fig. 6) in particular is not well captured at lower resolution. Thus, we will additionally construct "weekly" SST datasets for the full 1949-2003 period in two ways:

a)First, we will interpolate the monthly SST data onto the weekly time interval, similar to what is done for AMIP calculations, and use this dataset to construct a CLIM.

b)Then, for the 1981-2003 period we will regress the weekly NCEP SST against both weekly averaged atmospheric variables and the weekly interpolated SST determined in (a). This regression will be used to "correct" (more realistically, to improve) the weekly interpolated SST for the entire period; the resulting weekly SST dataset will again be used to construct a CLIM.

4. An additional LIM for the 1980-2002 period will be constructed with subsurface ocean information as well, using the NCEP Pacific Ocean Analysis Dataset. Note that adding subsurface variables has not been shown to improve the forecast skill of LIM of SSTs, most likely because the SST inverse model already implicitly includes the effects of all subsurface variables linearly related to the SSTs. This is of course not the same as saying that SST variability is due only to the *physics* of the ocean surface; the state of the ocean at depth is crucial, so including subsurface information in the LIM will allow diagnosis of the impact of these variables upon the variability and predictability of SSTs.
5. Finally, we will include some measures of coupling between the atmosphere and surface, such as surface moisture fluxes and wind stress anomalies. The former will be particularly useful for including the effects of land in the tropical belt. Our full state vector will thus represent the dominant EOFs of the weekly-averaged horizontal rotational and divergent circulation at five levels, the dominant EOFs of the column-integrated and column-varying heat sources and moisture sinks, the dominant EOFs of SSTs in the global tropical belt, and the dominant EOFs of surface fluxes in the global tropical belt. Given the limited data available, an important component of this analysis will be determining the best combination of retained variance for the EOF representation of each variable, and the robustness of the results with respect to changes in these truncations.

6. Error sensitivity analysis of the CLIMs (Penland and Sardeshmukh 1995a; Penland and Matrosova 2001) will be conducted, with respect to both data error and sampling limitations.
7. When the CLIM has been adequately tested and verified, real-time tropical forecasts of SST, P-E, and atmospheric diabatic and circulation anomalies on this higher subseasonal resolution will be released on the CDC website (current seasonal forecasts of SST alone are at http://www.cdc.noaa.gov/forecasts/IndoPacific.frcst.html).

This new coupled LIM will then be used to diagnose variability and predictability of the coupled tropical Indo-Pacific system.

1. The coupled LIM will allow an empirical determination of the form and impact of local air/sea coupling on the evolution of tropical intraseasonal atmospheric variability. ENSO's impact upon the variability of Q1 and Q2 subseasonal anomalies in general and upon MJO variability in particular will also be determined in this manner. This will also result in an empirical determination of the impact of air/sea coupling on the evolution of, and hence CLIM forecasts of, the MJO. The OLIM well captures the warming (cooling) of both the tropical Atlantic and Indian Oceans that follows the development of warming (cooling) in the eastern tropical Pacific (e.g., Penland 1996; Penland and Matrosova 1998), but by including atmospheric variables the CLIM will also provide understanding of the effect of changes in the Walker circulation upon the redistribution of heat in the Tropics.
2. Conversely, including weekly tropical SST anomalies explicitly in our LIM may not only improve subseasonal atmospheric forecast skill but also help in diagnosing and predicting the weekly tropical SST variations themselves more accurately.
3. We will estimate an average forecast signal-to-noise ratio for each model variable at each tropical grid point, and use it to estimate the potential predictability of weekly variations of that variable at that point. As in our previous predictability studies, we will also be able to quantify the case-to-case variations of predictability resulting from variations of the initial-state projection on the system's singular vectors. We will also combine these results with (1) above to determine how ENSO impacts predictability of the MJO and other Q1 and Q2 subseasonal anomalies.
4. We will determine the four-dimensional structure of such tropical modes of variability as the

MJO, Kelvin waves, equatorial Rossby (ER) waves, and mixed Rossby-gravity waves from our 54-year dataset of dynamically consistent winds, Q1, and Q2 fields, using the filter employed by Wheeler and Kiladis (1999). This will allow explicit comparison of these phenomena to either the deterministic LIM modes or (in the case of the faster components) to the structured stochastic forcing of those modes. Understanding how these phenomena impact the dynamical and noise structures is also important for the predictability analysis (e.g., Tippett and Chang 2003).

5. In conjunction with the statistics of the stochastic forcing determined from the Fluctuation-Dissipation Relation, the LIM will be used to generate a 1000-yr synthetic dataset of tropical atmospheric and oceanic variability using the method described in Penland and Matrosova (1994). Note that even though the LIM is generated from a short lag on the order of a few weeks, it nevertheless encompasses all timescales and dynamics operating on longer (potentially *much* longer) timescales. Thus, the power spectrum of different SST modes will be determined from this synthetic dataset. This will be compared to the observed spectrum (e.g., Fig. 1) to see if any observed variability (such as on decadal timescales) rises above this multivariate red noise background, or if such variability can be explained as resulting from spectral peaks inherent to the LIM. This will also allow an estimate of predictability on interdecadal timescales.
6. Note also that the SSTs from this dataset can be used to force AMIP-type AGCM experiments, and also the full dataset can be used to force AGCMs in relaxation experiments, to examine the extratropical response to realistic tropical forcing on not only subseasonal but also on interannual and even decadal time scales. The latter experiments in particular can be useful, since AGCMs commonly produce errors in the tropical precipitation (and consequently diabatic heating) response to tropical SST anomalies which complicates analysis of the tropical-extratropical relationship (e.g., Spencer and Slingo 2003).

Finally, the entire above analysis will be repeated on existing coupled GCM output from the NCAR CSM2 and CMIP2+ models to assess to what extent the relationships between the atmospheric and oceanic variables encapsulated in the LIM are correctly represented in comprehensive coupled models. The coupled GCMs of CMIP2+ all have daily output available (as opposed to earlier version of CMIP; see http://www-pcmdi.llnl.gov/cmip/cmip2plusann.html). We will directly compare the linear operators representing the dynamics of each of these models to the observed linear operator. We will determine how well each model represents the atmospheric, oceanic, and coupled portions of these operators, using the method described in section 1 above. We will also compare the statistics of the noise in each of these models to the statistics of the noise determined from observations. For each coupled GCM, we will compare the power spectra of the model output to the power spectra predicted by the CLIM of that model output, to again determine the amount of decadal variability that is above the multivariate red noise baseline of that coupled model. Finally, we will attempt to construct CLIMs from the output of the doubled-CO_2 experiments also available through CMIP2+. Problems with nonstationarity may make these calculations unsuccessful, but otherwise we can obtain an estimate of how anthropogenic change may impact the *dynamics* of the coupled system within the Tropics.

3. Timeline

We expect to follow the following approximate timeline over the three years covered by this proposal:

Year 1:Construct CLIMs, including robustness and significance tests of CLIMs. Conduct error sensitivity analysis.

Begin Wheeler/Kiladis analysis upon chi-corrected Q1, Q2, and circulation variables.

Year 2: Write up results of CLIM, including forecast skill and dominant dynamical structures.

Complete Wheeler/Kiladis analysis upon chi-corrected Q1, Q2, and circulation variables.

Write up results of Wheeler/Kiladis analysis upon chi-corrected Q1, Q2, and circulation variables.

Construct CLIMs from coupled GCM output.

Construct 1000-yr synthetic dataset of coupled tropical ocean/atmosphere.

Predictability analysis of CLIM.

Year 3: Analyze noise structures of CLIM, and relationship to faster tropical heating/circulation modes.

Write up noise and predictability analysis.

Construct CLIMs including subsurface data, for both observations and coupled GCMs.

Write up results of CLIM from coupled GCMs.

Write up results of CLIMs with subsurface data.

4. Readiness and budget justification

The P.I. and Co-P.I.s are well suited to undertake the proposed research, as is probably evident from their several publications on these topics in the last decade. The proposed project represents a natural extension of our previous work; as noted, the relevant component (uncoupled) LIM models are already built. All datasets which we plan to analyze, including the entire NCEP reanalyses dataset, the chi-corrected heating datatset, and the NCEP Pacific Ocean Analysis Dataset, are available in easily readable form here at CDC. The CMIP2+ dataset (used to make Fig. 1) is available under Diagnostic Subprojects (one approved (#44), a second currently pending) submitted to the CMIP panel.

The P.I. will assume overall responsibility for the completion of these tasks. The PI and co-PIs will all be actively involved in all parts of the project. A Professional Research Assistant, who will assist in all aspects of the project, will devote most of his/her time helping to generate and maintain the large datasets connected with the project, and doing the extensive tests of robustness and forecast skill required in the constructionof the LIM.

Drs. Newman, Sardeshmukh, and Penland request no direct support. Their salaries are covered under long-term funding to CDC through the Climate Dynamics and Experimental Prediction (CDEP) program of NOAA/OGP. Dr. Newman will devote approximately 2.5 months of his time, per year, to this project. Dr. Sardeshmukh will devote approximately 1.5 months of his time, per year, to this project. Dr. Penland will devote approximately 1 month of her time, per year, to this project. We are, however, requesting 7.5 months salary support for the project research assistant. One month support for a CDC-CIRES Computer System Support Personnel is requested to provide the technical support needed for essential computer hardware and software systems. Travel funds are requested to provide support to present our results at professional meetings. Materials and supplies will cover basic office supplies plus small software and storage media purchases.

References

DelSole, T., and A. Y. Hou, 1999: Empirical stochastic models for the dominant climate statistics of a general circulation model. *J. Atmos. Sci*., **56**, 3436—3456.

Fedorov, A. V., Harper, S. L., Philander, S. G., Winter, B., and Wittenberg, A., 2003: How predictable is El Niño? *Bull. Amer. Meteor. Soc.*, **84**, 911-919.

Lin, J., Mapes, B., Zhang, M., and Newman, M., 2003: Stratiform precipitation, vertical heating profiles, and the Madden-Julian Oscillation. Submitted to *J. Atmos. Sci.*

Meehl, G.A., G.J. Boer, C. Covey, M. Latif, and R.J. Stouffer, 2000: The Coupled Model Intercomparison Project (CMIP). *Bull. Amer. Meteorol. Soc.*, **81**, 313-318.

Newman M., P. D. Sardeshmukh, and J. W. Bergman, 2000: An assessment of the NCEP, NASA and ECMWF reanalyses over the Tropical West Pacific warm pool. *Bull. Amer. Meteor. Soc.*, **81**, 41-48.

Newman, M., P. D. Sardeshmukh, C. R. Winkler, and J. S. Whitaker, 2003: A study of subseasonal predictability. *Mon. Wea. Rev.*, **131**, 1715-1732.

Penland, C., 1989: Random forcing and forecasting using principal oscillation pattern analysis. *Mon. Wea. Rev.*, **117**, 2165—2185.

Penland, C., 1996: A stochastic model of IndoPacific sea surface temperature anomalies. *Physica D*, **98**, 534--558.

Penland, C., and M. Ghil, 1993: Forecasting Northern Hemisphere 700-mb geopotential heights using principal oscillation patterns. *Mon. Wea. Rev.*, **121**, 2355—2372.

Penland, C., and L. Matrosova, 1994: A balance condition for stochastic numerical models with application to the El Niño - Southern Oscillation, *J. Climate*, **7**, 1352-1372.

Penland, C., and L. Matrosova, 1998: Prediction of tropical Atlantic sea surface temperatures using Linear Inverse Modeling, *J. Climate*, **11**, 483-496.

Penland, C., and L. Matrosova, 2001: Expected and Actual Errors of Linear Inverse Modeling Forecasts, *Monthly Weather Review*, **129**, 1740-1745.

Penland, C., and P. D. Sardeshmukh, 1995a: Error and sensitivity analysis of geophysical eigensystems, *J. Climate*, **8**, 1988-1998.

Penland, C., and P. D. Sardeshmukh, 1995b: The optimal growth of tropical sea surface temperature anomalies. *J. Climate*, **8**, 1999—2024.

Reynolds, R.W., N.A. Rayner, T.M. Smith, D.C. Stokes, and W. Wang, 2002: An Improved In Situ and Satellite SST Analysis for Climate. *J. Climate*

Sardeshmukh, P. D., 1993: The baroclinic chi problem and its application to the diagnosis of atmospheric heating rates. *J. Atmos. Sci.*, **50**, 1099—1112.

Sardeshmukh, P. D., M. Newman, and C. R. Winkler, 1999: Dynamically consistent estimates of diabatic heating. Proceedings, *24th Annual Climate Diagnostics and Prediction Workshop*, Tucson, AZ, 172—175.

Sardeshmukh, P. D., G. P. Compo, and C. Penland, 2000: Changes of probability associated with El Niño. *J. Climate*, **13**, 4268-4286.

Spencer, H., and J. M. Slingo, 2003: The simulation of peak and delayed ENSO teleconnections. *J. Climate*, **16**, 1757-1774.

Tippett, M. K., and P. Chang, 2003: Some theoretical considerations on predictability of linear stochastic dynamics. *Tellus*, **55**, 148-157.

Winkler, C. R., M. Newman, and P. D. Sardeshmukh, 2001: A linear model of wintertime low-frequency variability. Part I: Formulation and forecast skill. *J. Climate*, **14**, 4474-4494.

PRASHANT D. SARDESHMUKH

CURRICULUM VITAE July 2003

Mailing Address NOAA-CIRES Climate Diagnostics Center
R/CDC, 325 Broadway
Boulder, CO 80305-3328, USA
Telephone (303) 497-6248
FAX (303) 497-7013
E-mail Prashant.D.Sardeshmukh@noaa.gov

EDUCATION AND PROFESSIONAL QUALIFICATIONS

Current Position:
Associate Director (Jan 99 -) and Senior Research Scientist (Aug 96 -)
NOAA-CIRES Climate Diagnostics Center, Boulder, CO

1999-2001
Editor, *Journal of the Atmospheric Sciences*

August 1990 - November 1990
Joint Director, National Center for Medium Range Weather Forecasting (NCMRWF), New Delhi, India. The post was equivalent to that one step below the Director General of the India Meteorological Department.

January 1989 - July 1996
Research Associate, CIRES, University of Colorado at Boulder, Boulder, CO 80309

October 1986 - December 1988
Visiting Scientist/Consultant, Research Department, European Centre for Medium Range Weather Forecasts (ECMWF), Reading, Berkshire, U.K.

1982-86 Gassiot Committee (Royal Society) Post-Doctoral Research Fellow in the Department of Meteorology, University of Reading, U.K. Worked on a joint project of the University with the U.K. Meteorological Office concerned with conducting diagnostic studies of the global circulation using ECMWF data.
Principal Investigator: Brian J. Hoskins, FRS.

1980, 1983 : M.A and Ph.D in Geophysical Fluid Dynamics from Princeton University, U.S.A.
Graduate Student in the Geophysical Fluid Dynamics Program.
Research carried out at the Geophysical Fluid Dynamics Laboratory of NOAA.
Title of thesis: Mechanisms of Monsoonal Cyclogenesis.
Supervisor: Isaac M. Held.

1978 Master of Science in Physics (5-year integrated Bachelor's plus Masters course after Higher Secondary) from the Indian Institute of Technology, Kanpur, India.
First Class with Distinction.

REFEREED PUBLICATIONS (since 1998)

Newman, M., Sardeshmukh, P.D., Winkler, C.R., and J.S. Whitaker, 2003:
A study of subseasonal predictability.
Mon. Wea. Rev., **131**, 1715-1732.
Barsugli, J.J., and P.D. Sardeshmukh, 2002:
Global atmospheric sensitivity to tropical SST anomalies throughout
the Indo-Pacific basin. *J. Climate*, **15**, 3427-3442.
Ricciardulli, L., and P.D. Sardeshmukh, 2002:
Local Time- and Space Scales of Organized Tropical Deep Convection.
Journal of Climate, **15**, 2775–2790.
Winkler, C. R., M. Newman, and P. D. Sardeshmukh, 2001:
A linear model of wintertime low-frequency variability.
Part I: Formulation and forecast skill. *J. Climate*, **14**, 4474-4494.
Compo, G.P., Sardeshmukh, P.D., and C. Penland, 2001:
Changes of subseasonal variability associated with El Niño.
J. Climate, **14**, 3356-3374.
Sardeshmukh, P.D., Penland, C., and M. Newman, 2001:
Rossby waves in a fluctuating medium.
In *Stochastic Climate Model*s, P. Imkeller and J. -S. von Storch (Eds).
Progress in Probability, **49**, Birkhaueser, Basel, 369-384.
Sardeshmukh, P.D., Compo, G.P., and C. Penland, 2000:
Changes of probability associated with El Nino.
J. Climate, **13**, 4268-4286
Smith, C.A., and P.D. Sardeshmukh, 2000:
The effect of ENSO on the intraseasonal variance of surface temperature in winter.
Int.J.Climatol. **20**, 1543-1557.
Huang, H.P. and P. D. Sardeshmukh, 2000:
Another look at the annual and semiannual cycles of atmospheric angular momentum.
J. Climate, **13**, 3221-3238.
Newman, M., Sardeshmukh, P.D., and J. W. Bergman, 2000:
An assessment of the NCEP, NASA, and ECMWF Reanalyses over the Tropical West
Pacific Warm Pool. *Bull. Amer. Meteor. Soc*., **81**, 41-48.
Huang, H.P., Sardeshmukh, P.D., and K.M. Weickmann, 1999:
The balance of global atmospheric angular momentum in a long-term dataset.
J. Geophys. Res., **104**, 2031-2040.
Barsugli, J.J., Whitaker, J.S., Loughe, A., and Sardeshmukh, P.D., and Z. Toth, 1999:
The effects of the 1997-98 El Niño on individual large-scale weather events.
Bull. Amer. Meteor. Soc., **80**, 1399-1411.
Newman, M., and P. D. Sardeshmukh, 1998:
The impact of the annual cycle upon the North Pacific/North American response
to low frequency forcing. *J. Atmos. Sci., 55, 1336-1353.*
Whitaker, J.S., and P. D. Sardeshmukh, 1998:
A linear theory of extratropical synoptic eddy statistics.
J. Atmos. Sci, 55, 237-258.
Hall, N.M.J., and P. D. Sardeshmukh, 1998:
Is the time mean Northern Hemisphere flow baroclinically unstable?
J. Atmos. Sci. 55, 41-56.

VITAE

Name:	Matthew Newman
Address:	NOAA-CIRES Climate Diagnostics Center Mail Code R/CDC1, 325 Broadway Boulder, CO 80305-3328, U.S.A
Telephone:	(303) 497-6233
FAX:	(303) 497-7013
Email:	matt.newman@noaa.gov

CURRENT POSITION:

Research Scientist III (March 2002 - present).
Cooperative Institute for Research in the Environmental Sciences (CIRES),
University of Colorado, Boulder, CO

PREVIOUS POSITION:

Research Scientist II (March 1999 - March 2002).
Cooperative Institute for Research in the Environmental Sciences (CIRES),
University of Colorado, Boulder, CO

Research Associate (November 1991 - March 1999).
Cooperative Institute for Research in the Environmental Sciences (CIRES),
University of Colorado, Boulder, CO

EDUCATION:

Ph.D., Atmospheric Science, October 1991.
University of Washington, Seattle WA.
Dissertation title: Model Studies of the Middle Atmosphere of Venus
Chairperson of the Supervisory Committee: Professor C. B. Leovy

B.S., Atmospheric Science, June 1982.
University of California at Los Angeles, Los Angeles CA.

<u>Refereed publications last three years plus five additional publications:</u>

Newman, M., G. P. Compo, M. A. Alexander, 2003: ENSO-forced variability of the Pacific Decadal Oscillation. *J. Climate*, in press.

Sardeshmukh, P. D., C. Penland, and M. Newman, 2003: Drift induced by multiplicative red noise with application to climate. *Europhysics Letters*, in press.

Newman, M., P. D. Sardeshmukh, C. R. Winkler, and J. S. Whitaker, 2003: A study of subseasonal predictability. *Mon. Wea. Rev.*, **131**, 1715-1732.

Alexander, M. A., I. Bladé, M. Newman, J. R. Lanzante, N.-C. Lau, and J. D. Scott, 2002: The atmospheric bridge: the influence of ENSO teleconnections on air-sea interaction over the global oceans. *J. Climate*, **15**, 2205-2231.

Winkler, C. R., M. Newman, and P. D. Sardeshmukh, 2001: A linear model of wintertime low-frequency variability. Part I: Formulation and forecast skill. *J. Climate*, **14**, 4474-4494.

Sardeshmukh, P. D., C. Penland, and M. Newman, 2001: “Rossby waves in a fluctuating medium.” In *Stochastic Climate Models*, ed. P. Imkeller and J.-S. von Storch, Progress in Probability, **49**, Birkhaueser, Basel, pp. 369-384.

Newman, M., M. A. Alexander, C. R. Winkler, J. D. Scott, and J. J. Barsugli, 2000: A linear diagnosis of the coupled extratropical Ocean-Atmosphere system in the GFDL GCM. *Atmos. Sci. Lett.*, **1**, 14-25.

Newman M., P. D. Sardeshmukh, and J. W. Bergman, 2000: An assessment of the NCEP, NASA and ECMWF reanalyses over the Tropical West Pacific warm pool. *Bull. Amer. Meteor. Soc.*, **81**, 41-48.

Newman, M. and P. D. Sardeshmukh, 1998: The impact of the annual cycle upon the North Pacific/North American response to low frequency forcing. *J. Atmos. Sci.*, **55**, 1336-1353.

Newman, M., P. D. Sardeshmukh, and C. Penland, 1997: Stochastic forcing of the wintertime extratropical flow. *J. Atmos. Sci.*, **54**, 435-455.

Newman, M. and P. D. Sardeshmukh, 1995: A caveat concerning Singular Value Decomposition. *J. Climate*, **8**, 352-360.

Abbreviated Curriculum Vitae for

Cecile Penland

Current position: Physical Scientist
NOAA-CIRES, Climate Diagnostics Center
R/CDC1
325 Broadway
Boulder, CO 80303-3328
Telephone: (303) 497-6234; E-mail: Cecile.Penland@noaa.gov

Education:

PhD., Physics, The University of Texas at Austin, December 1984.
M.S., Physics, Florida Atlantic University, Boca Raton, FL, August, 1977.
B.S., Physics, Florida Atlantic University, Boca Raton, FL, March, 1975.

Publications from last three years:

Monthly contributor to Forecasters' Forum section of Climate Diagnostics Bulletin, National Weather Service, NMC, Washington D.C.

Seasonal contributor to *Experimental Long-lead Forecast Bulletin*, Center for Ocean-Land Atmosphere Studies, Calverton, MD.

Ewald, B., C. Penland, and R, Temam, 2003: Accurate Integration of Stochastic Climate Models. *Monthly Weather Review*, in press.

Sardehmukh, P., C. Penland, and M. Newman, 2003: Drifts induced by multiplicative red noise with application to climate. *Europhysics Letters*, in press.

Penland, C., 2003: Noise out of chaos and why it won't go away. *Bulletin of the American Meteorological Society*, **84**, 921-925.

Penland, C., 2003: A Stochastic Approach to Nonlinear Dynamics: A Review (Electonic supplement to 'Noise out of chaos and why it won't go away'). *Bulletin of the American Meteorological Society*, **84**, ES43-ES52.

Compo, G., P. Sardeshmukh, and C. Penland, 2002: Predictability of anomalous storm tracks. *The Climate Report*, **3**, 2-6.

Penland, C., 2002: On the Perception of Probabilistic Forecasts, in *Facts and Speculation about La Niña and its Societal Impacts*. ed. M.H. Glantz, United Nations University Press, Tokyo, 253-255 (reviewed).

Sura, P., and C. Penland, 2002: Sensitivity of a Double-Gyre Ocean Model to Details of Stochastic Forcing, *Ocean Modelling*, **4**, 327-345.

Sardeshmukh, P., C. Penland and M. Newman, 2001: Climate drifts and variability induced by noise, *Proc. 25th Climate Diagnostics Workshop*, Palisades, NY, Oct. 2000. U.S. Dept. Commerce, Springfield, VA.

Compo, G. P., P. D. Sardeshmukh, and C. Penland, 2001: Changes of Subseasonal Variability associated with El Nino, *J. Climate*, **14**, 3356-3374.

Penland, C., and L. Matrosova, 2001: Expected and Actual Errors of Linear Inverse Modeling Forecasts, *Monthly Weather Review*, **129**, 1740-1745.

Sardeshmukh, P. D., C. Penland, and M. Newman, 2001: Rossby waves in a fluctuating medium, in *Stochastic Climate Models*, ed. P. Imkeller and J.-S. von Storch, *Progress in Probability*, **49**, Birkhaueser, Basel (reviewed).

Sardeshmukh, P. D., G. P. Compo, and C. Penland, 2000: Changes of probability associated with El Niño, *J. Climate*, **13**, 4268-4286.

Weickmann, K., W. A. Robinson, and C. Penland, 2000: Stochastic and oscillatory forcing of global atmospheric angular momentum, *J. Geophysical Research*, **105**, 15 543 - 15 557.

Penland, C., and L. Matrosova, 2000: Nonnormal El Nino Evolution in the Early 20th Century, *Proc. 24st Climate Diagnostics Workshop*, Tucson, AZ, 1-5 Nov., 1999. U. S. Dept. Commerce. Springfield, VA.

Penland, C., M. Fluegel, and P. Chang, 2000: The identification of dynamical regimes in an intermediate coupled ocean-atmosphere model, *J. Climate*, **13**, 2105-2115.

Five other selected publications:

Penland, C., and L. Matrosova, 1998: Prediction of tropical Atlantic sea surface temperatures using Linear Inverse Modeling, *J. Climate*, **11**, 483-496.

Penland, C., 1996: A stochastic model for IndoPacific sea surface temperature anomalies. *Physica D*, **98**, 534-558.

Penland, C., and P. D. Sardeshmukh, 1995b: The optimal growth of tropical sea surface temperature anomalies, *J. Climate*, **8**, 1999-2024.

Penland, C., and P. D. Sardeshmukh, 1995a: Error and sensitity analysis of geophysical eigensystems, *J. Climate*, **8**, 1988-1998.

Penland, C., and L. Matrosova, 1994: A balance condition for stochastic numerical models with application to the El Niño - Southern Oscillation, *J. Climate*, **7**, 1352-1372.

Current and pending grants, starting in FY 2004

Prashant Sardeshmukh

Agency	Project Title	Amount	Period	Months
NOAA-C&GC	Predictability of anomalous Northern Hemisphere storm tracks from seasonal to decadal timescales (P.I.: G. P. Compo; Co-P.I.s: P. D. Sardeshmukh)		2004-2007	1 per year
NOAA-C&GC	Subseasonal predictability of the coupled tropical Indo-Pacific (this proposal) (P.I.: P. D. Sardeshmukh; Co-P.I.s: M. Newman, C. Penland)	$219,000	2004-2007	1.5 per year

Matthew Newman

Agency	Project Title	Amount	Period	Months
NOAA-C&GC	Impacts of Atmospheric Bridges upon the Extratropical Variability and Predictability Related to ENSO (P.I.: M. Newman; Co-P.I.s: M. Alexander, I. Blade)	$317,846	2003-2006	3 per year
NOAA-C&GC	Subseasonal predictability of the coupled tropical Indo-Pacific (this proposal) (P.I.: P. D. Sardeshmukh; Co-P.I.s: M. Newman, C. Penland)	$219,000	2004-2007	2.5 per year

B U D G E T Title: Subseasonal Predictability of the Coupled Tropical IndoPacific

Institution: NOAA-CIRES Climate Diagnostics Center
NOAA/OAR
325 Broadway
Boulder, CO 80305
Duration: February 1, 2004-January 31, 2007

A. SALARIES AND WAGES	Staff-Months	Year One	Year Two	Year Three	**Total**
PI: Prashant Sardeshmukh	1.5	No Cost	No Cost	No Cost	No Cost
Co-PI: Matt Newman	2.5	No Cost	No Cost	No Cost	No Cost
Co-PI: Cecile Penland	1.0	No Cost	No Cost	No Cost	No Cost
Professional Research Assistant	7.5	34335	36052	37854	**108241**
Computer System Support Personnel	1.0	5835	6457	6780	**19072**
Total Salaries and Wages		40170	42509	44634	**127312**
B. FRINGE BENEFITS					
Salaries and Wages: 19.25% and $358/mo		10776	11314	11880	**33970**
Total Salary, Wages, Benefits (A-B)		50946	53823	56514	**161283**
C. PERMANENT EQUIPMENT		0	0	0	**0**
D. EXPENDABLE EQUIPMENT		0	0	0	**0**
E. TRAVEL					
1. Domestic		1600	1680	1764	**5044**
2. International		0	0	0	**0**
Total Travel		1600	1680	1764	**5044**
F. PUBLICATION (Page charges; $115 per page)		0	1783	1872	**3655**
G. OTHER COSTS					
1. Computer Services/Maintenance		2714	2956	3104	**8774**
2. Materials and Supplies		1078	1139	1196	**3414**
3. Communication/Duplication		200	210	221	**631**
Total Other Costs		3992	4306	4521	**12819**
TOTAL DIRECT COSTS (A through G)		56538	61592	64671	**182800**
INDIRECT COSTS (CIRES 20%)		11308	12318	12934	**36560**
TOTAL COSTS		67845	73910	77605	**219360**

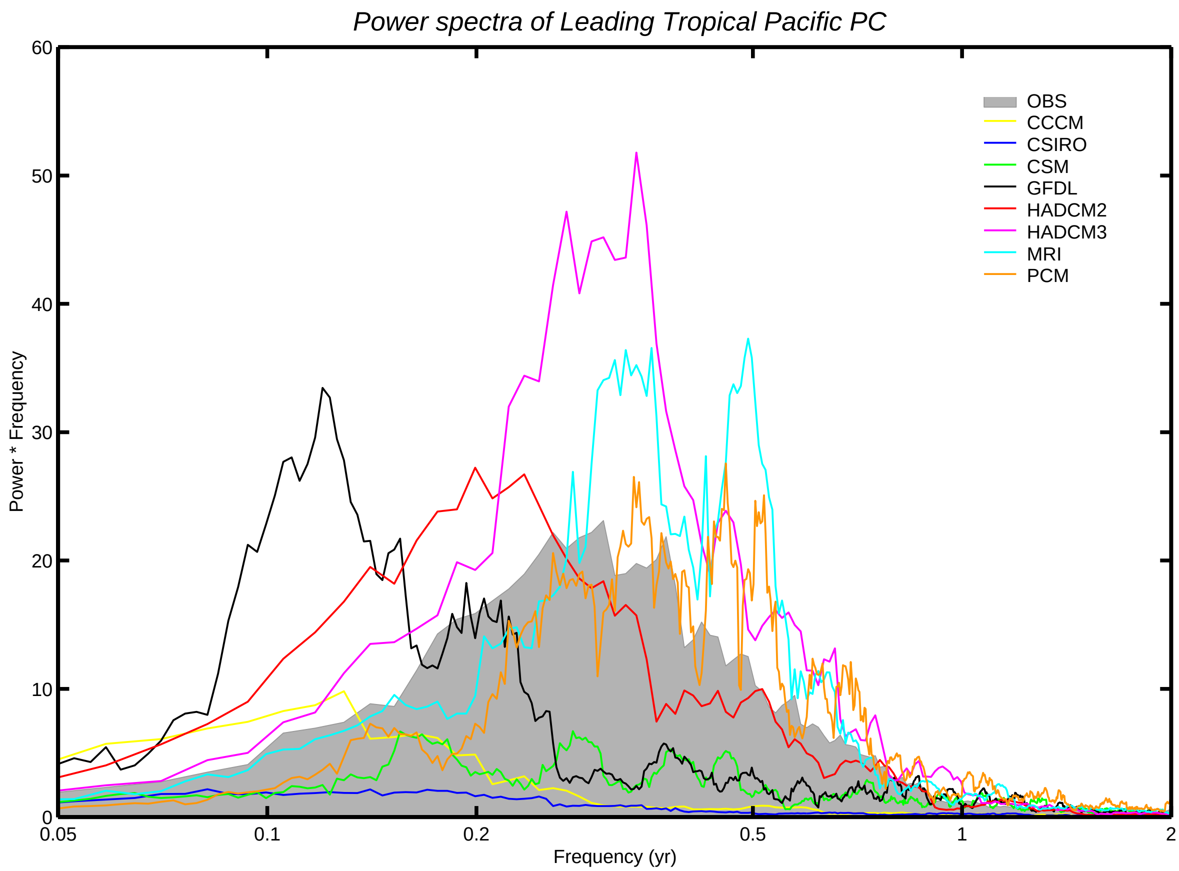

Figure 1: Power spectra of the leading principal component (PC) of Tropical Pacific SST from observations (HADIST dataset) and eight different coupled GCMs from CMIP 2+.

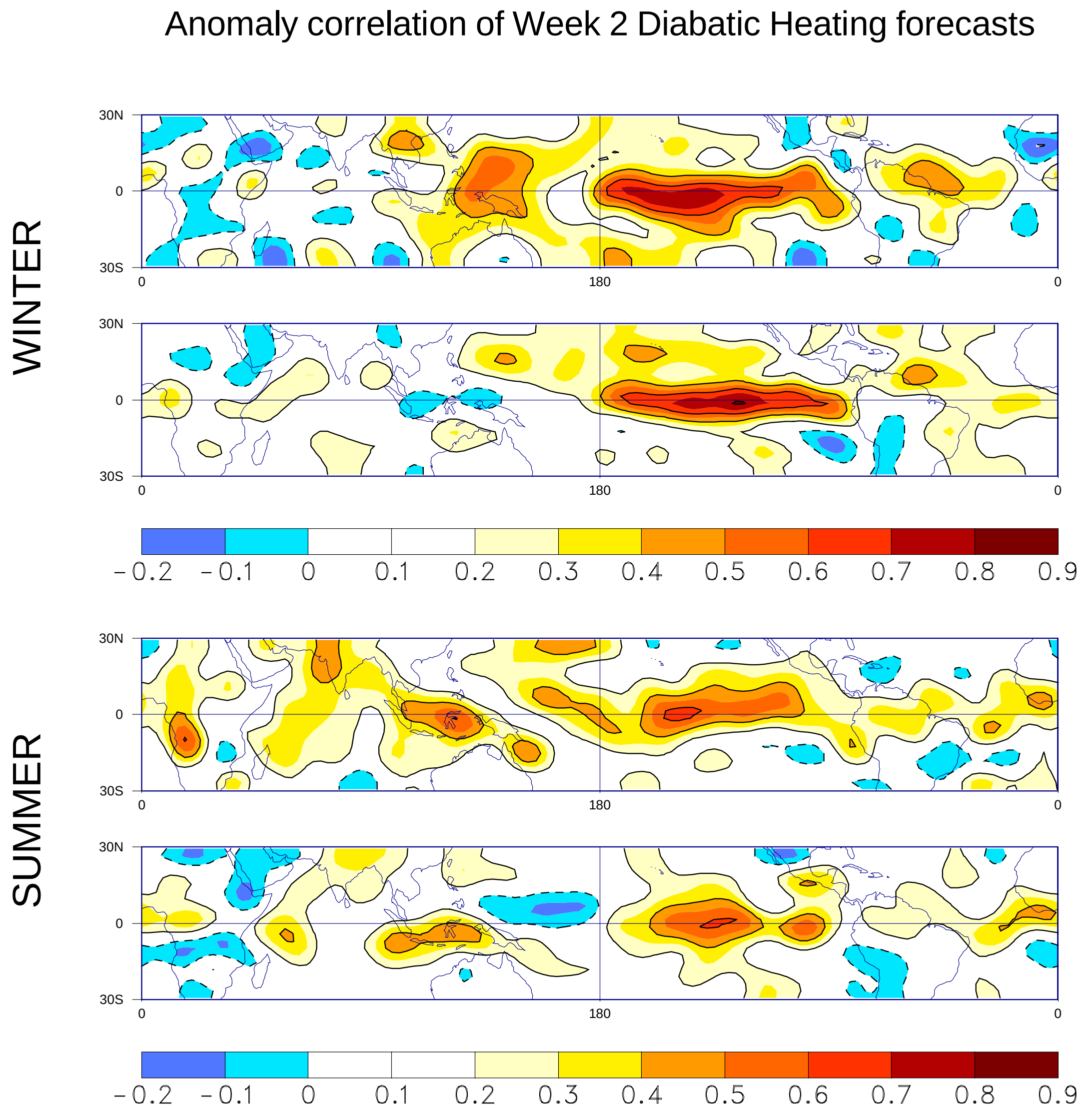

Figure 2. Comparison of local anomaly correlation of column-integrated tropical diabatic heating week 2 forecasts for the LIM and the MRF98, for the years 1979-2000. The MRF forecasts come from the 22-year "Reforecast dataset" available at http://www.cdc.noaa.gov/~jsw/refcst. Top: wintertime. Bottom: summertime. Contour (shading) interval is 0.2 (0.1). From Newman et al. (2003).

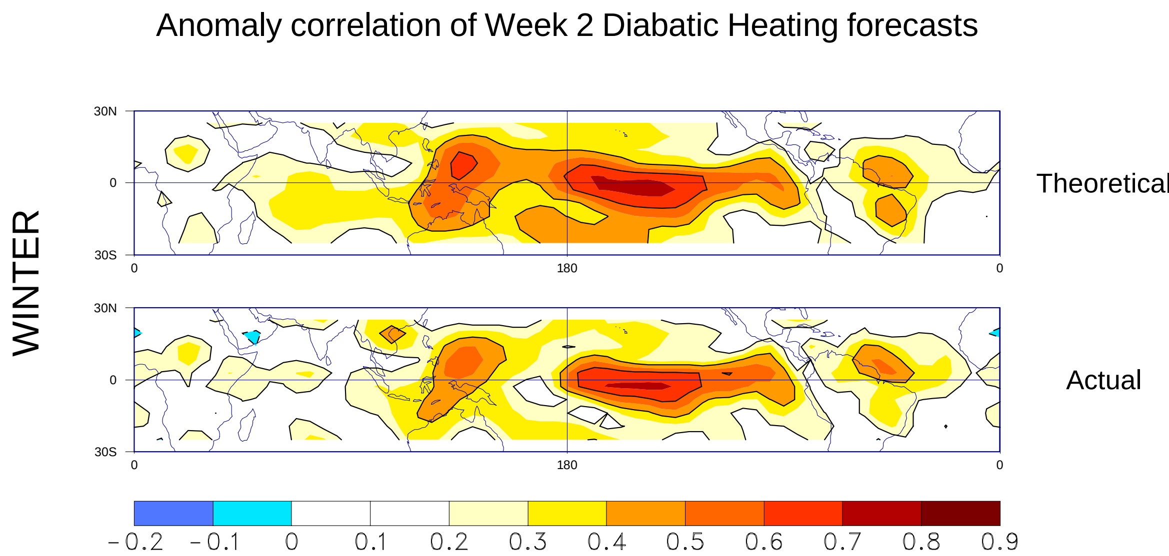

Figure 3. Local anomaly correlation of week-2 column-integrated tropical diabatic heating forecasts for the ALIM, for the winters of 1969-2000: (top) theoretical mean predictability limit ρ_∞; (bottom) actual skill from 30 years of jacknifed forecasts. Contour (shading) interval is 0.2 (0.1).

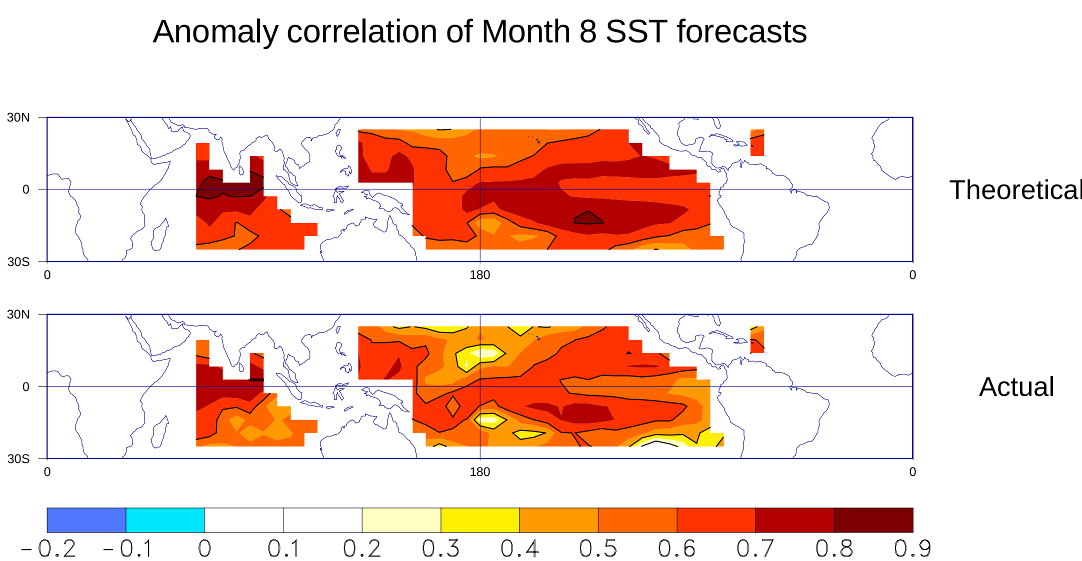

Figure 4. Local anomaly correlation of month-8 SST forecasts for the OLIM, for the years 1950-2002: (top) theoretical mean predictability limit ρ_∞; (bottom) actual skill from 53 years of jacknifed forecasts. Contour (shading) interval is 0.2 (0.1).

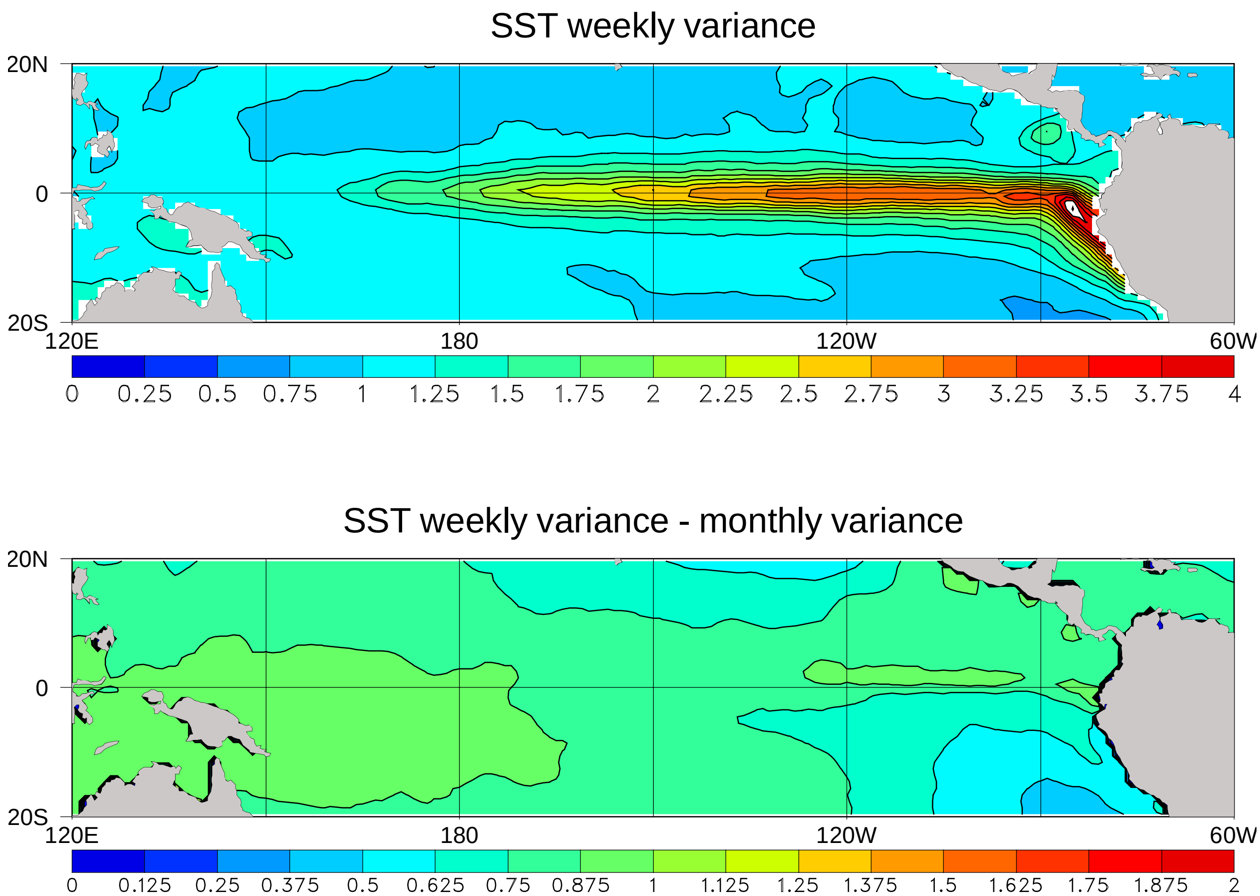

Figure 5:(Top) Variance of weekly mean SST, 1982-2002. (Bottom) Difference between variance of weekly mean SST anomalies and monthly mean SST anomalies. Contour interval 0.25 K^2.

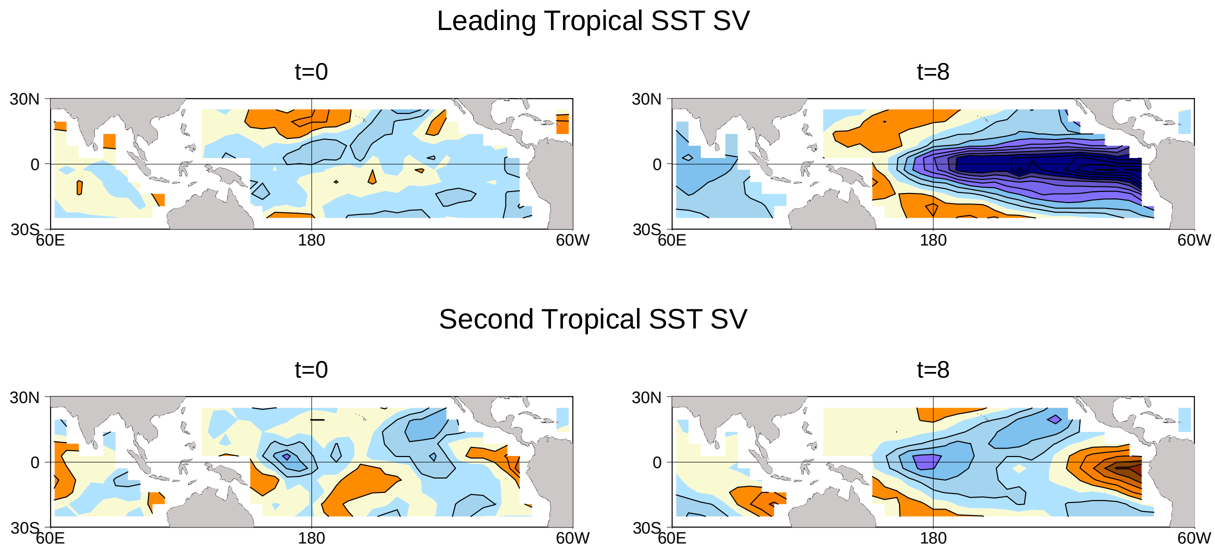

Figure 6: First two singular vectors for $\tau = 8$ months. (left) Initial SST anomaly (right singular vector); (right) SST anomaly at month 8 (left singular vector). Contour interval is 0.05 K; orange shading denotes positive values and blue shading denotes negative values.

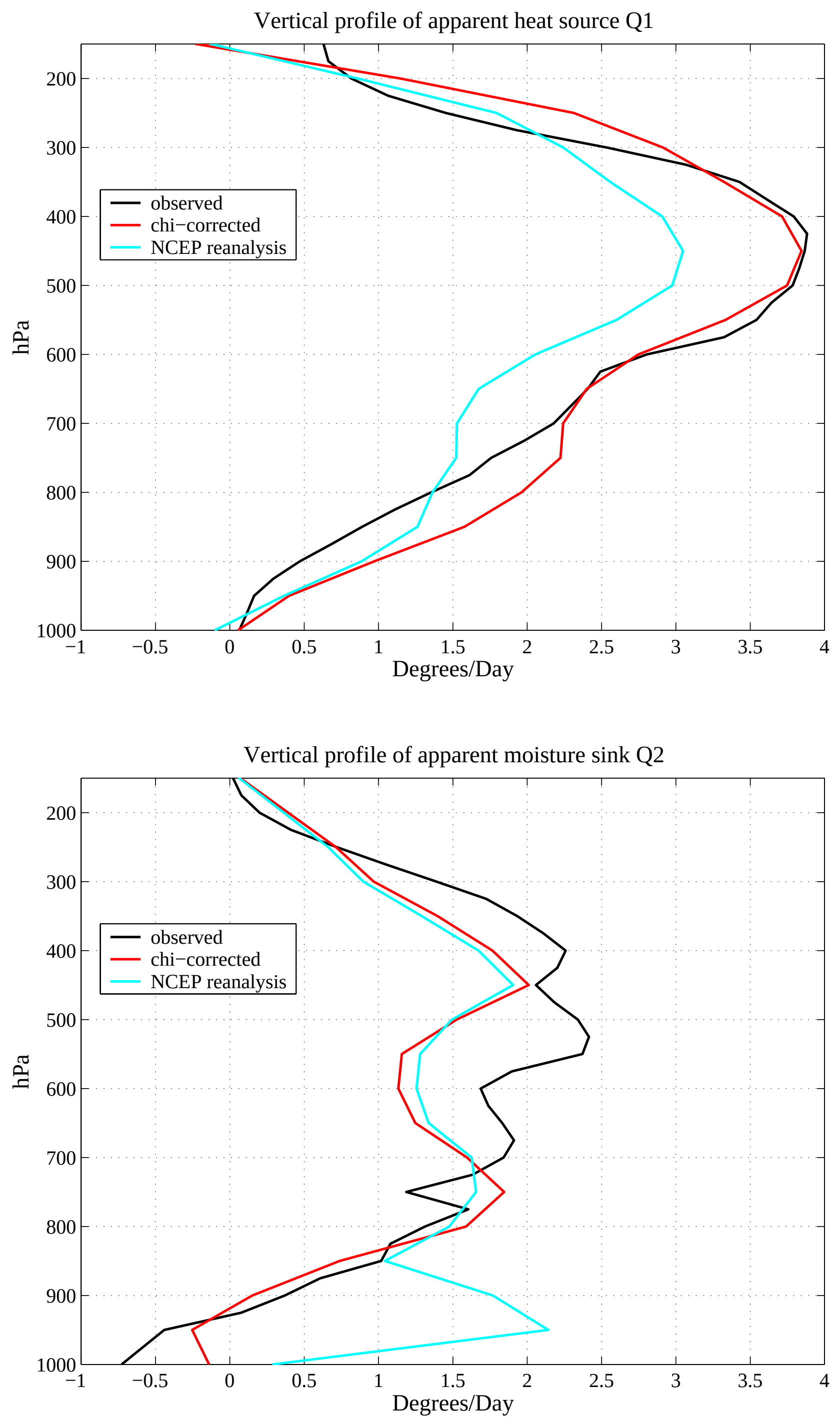

Figure 7: The vertical profiles of the chi-corrected heat source, Q1, and moisture sink, Q2, during the Intensive Observing Period (1 Nov 1992 - 28 Feb 1993) of TOGA-COARE, compared with the NCEP reanalysis and observed data, an updated version of Johnson and Lin (1997) taken over the Intensive Flux Array (IFA) region of COARE. The NCEP reanalysis and chi-corrected data were taken from an analysis gridpoint near the center of the IFA region (1.4S, 155E).